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MEASUREMENT PROBLEMS RELATED TO SOLID ROCKET COMBUSTION INSTABILITY

by

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ABSTRACT. A review is presented of the classes of instability, conditions favoring each class, experimental measurements recognized to diagnose each class, and problems in conducting such measurements.

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FOREWORD

This report was written for the solid rocket propulsion engineer as a practical guide to measurement of solid propellant rocket motor instability. As such, it stresses aspects of instability and measurement problems that are likely to be encountered on the motor test stand rather than in a scientific laboratory research endeavor.

The information contained in this report was presented at the Fifth Annual Meeting of the Interagency Chemical Rocket Propulsion Group (ICRPG) Static Test Panel Working Group, 18-19 October 1967, in Sacramento, California (CPIA Publication No. 161). It is being released in its present form to provide wider distribution and to make it more accessible to persons responsible for solid propellant rocket motor development.

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INTRODUCTION

Combustion instability has hampered development of a variety of solid propellant motors over the past 25 years. It continues to be a problem today in spite of a great increase of knowledge regarding its causes and cures. At present, as in the past, motor design and test personnel are faced with the possibility that their next motor firing will be unstable. This is particularly the case following changes in motor or grain design or alteration of propellant composition.

The intent of this paper is to emphasize the importance of proper instability measurement and the methods used to attain that goal. The subject includes consideration of the nature of combustion instability, with particular attention being paid to the character of gas oscillations in the motor, the determination of proper transducers for detecting instability, and the choices to be made regarding signal conditioning and recording equipment. Other items of interest include the calculation of oscillation frequencies, conditions which favor particular modes and frequencies of instability, and methods used to analyze instability data.

NATURE OF COMBUSTION-DRIVEN GAS OSCILLATIONS

Combustion instability is the result of an interaction between gas flow in the motor and energy release from the combustion zone such that small flow disturbances are amplified into larger ones (Ref. 1 and 2). The flow disturbances involve pressure and velocity variations in various parts of the motor which are usually, but not always, periodic. Two general classes of gas oscillation are observed: (1) acoustic oscillations in which the gas vibrates in one or more standing acoustic wave modes of the motor and (2) nonacoustic oscillations which are related to the gas discharge characteristics of the motor (Ref. 3 and 4).

ACOUSTIC INSTABILITY

This class of instability is the type most often encountered in solid propellant rocket motors. The frequency of oscillation and distribution of the oscillating component of pressure and of velocity are determined by the internal motor dimensions, the "mode" of oscillation, and the speed of sound in the gas (Ref. 5). The environment imposed by pressure and velocity oscillations in the motor often result in significant deviations of motor pressure from the desired value due to the

burning rate being altered from its normal value as shown in Fig. 1 (Ref. 6 and 7). The burning rate is always increased in the region of velocity variations and it is always reduced in the region of pressure oscillations (Ref. 8 and 9). The <u>net</u> effect on the burning rate during instability may be positive, negative, or neutral, depending on the propellant composition, the placement of burning surfaces in the motor, and the structure of the gas oscillations. It is usually the motor pressure deviations that make instability unacceptable.

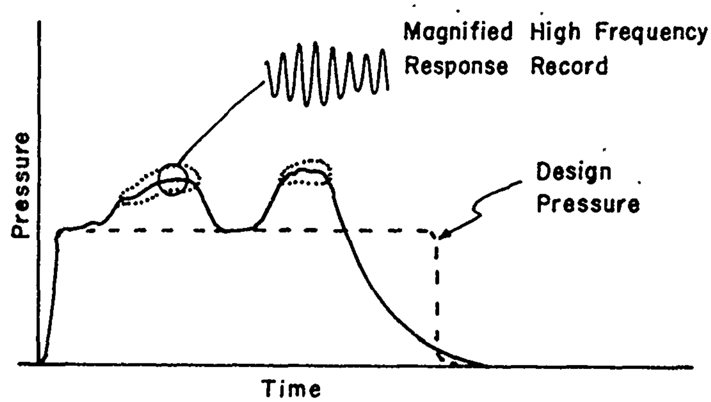


FIG. 1. Sketch of Rocket Motor Pressure-Time History Showing Typical Effect of Combustion Instability. Gas oscillations in the motor invariably accompany deviation of pressure from design value when instability is the cause of trouble.

Acoustic oscillations can be classified into two general categories: (1) longitudinal oscillations, in which the gas moves in a direction parallel to the motor axis and (2) transverse oscillations in which the gas moves perpendicularly to the motor axis (Ref. 5 and 10). One of the difficulties encountered in considering acoustic instability is the complex internal geometry characteristic of most rocket motors. In the following, therefore, it will be assumed that the motor interior can be approximated by a circular cylinder which is closed at both ends. The emphasis in the following will be on a qualitative description of the types of acoustic oscillation, means of calculating frequencies, and optimum locations for pressure transducers.

LONGITUDINAL OSCILLATIONS

The simplest type of longitudinal oscillation, called the "first mode" or sometimes the "fundamental mode", consists of gas motion parallel to the motor axis with a maximum velocity (velocity antinode) at the

center of the motor and maxima in pressure (pressure antinodes) at the ends of the motor (Fig. 2). As is the case with all types of standing acoustic waves, the envelope of pressure oscillations varies continuously with distance and higher order modes are possible (Fig. 3), each of which has a particular pressure distribution and frequency.

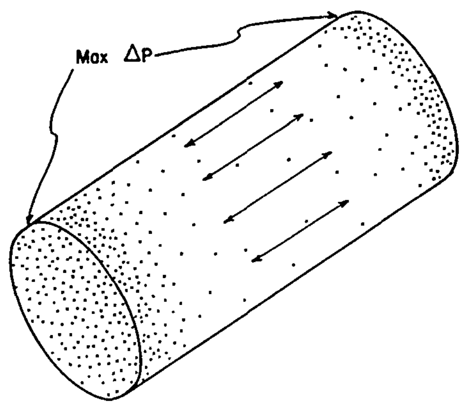


FIG 2. Longitudinal (Axial Mode) Oscillations Involve Gas Motion Parallel to the Motor Axis. Regions of maximum pressure variation (pressure antinodes) alternately occur at the ends of the motor. Arrows indicate direction of gas motion in the region where gas velocity oscillations have maximum values.

The frequency of a longitudinal mode is calculated from the relation

$$f = \frac{\lambda a}{2L} ,$$

where f is the frequency, λ is a positive integer (the mode number), a is the velocity of sound in the gas, and L is the length of the motor (Ref. 5). The various mode frequencies in real motors seldom bear a simple integral relationship to each other that is assumed here. The variations that are observed are due partly to complications induced by the geometry of real motors, and partly to the effects of oscillatory amplitudes much larger in magnitude than assumed by acoustic theory.

Optimum pressure transducer locations for measurement of this type of instability are at either end of the motor, since <u>every</u> longitudinal mode has a pressure antinode at these places. Generally, the head end is to be preferred since there are no net gas flow complications as are likely to be encountered in the nozzle region.

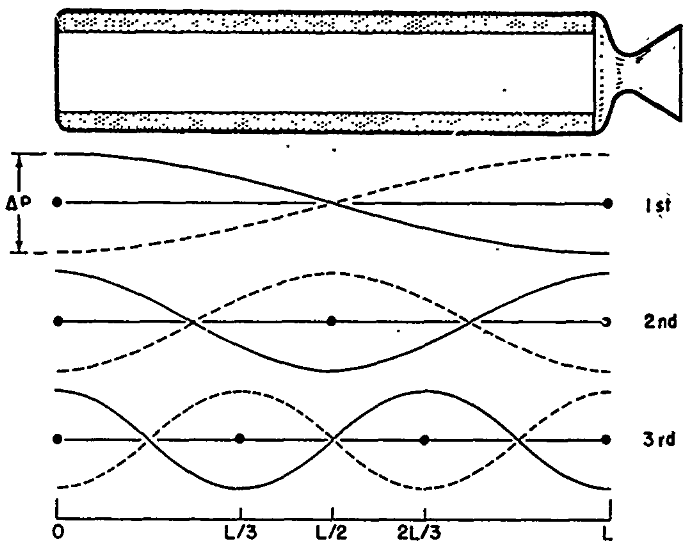


FIG. 3. Acoustic Pressure Distribution for Longitudinal Oscillations. Examples for the first three modes are shown. Small, heavy circles denote pressure antinode locations. Solid lines indicate the pressure distribution at an instant in time when the pressure at the head end is a maximum while the dashed line represents the distribution a half cycle later.

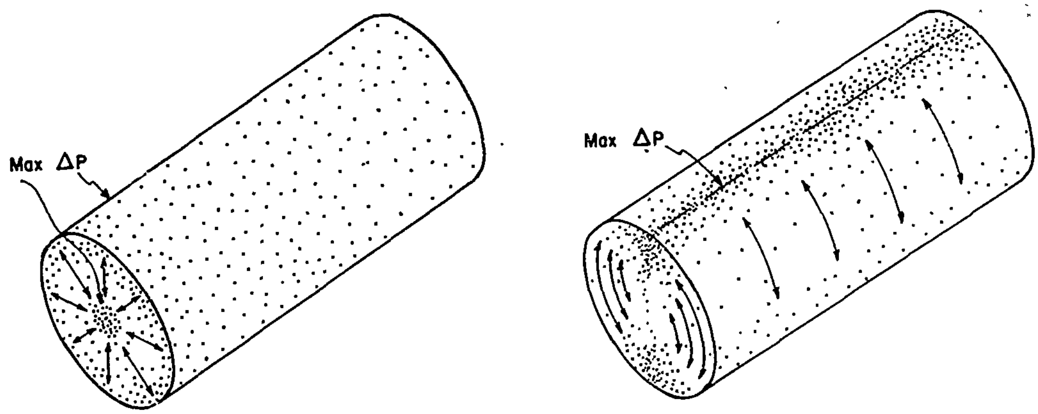
TRANSVERSE OSCILLATIONS

Two types of transverse oscillations are possible in a cylindrical geometry: (1) radial oscillations in which the gas moves in and out along radii of the motor and (2) tangential oscillations which involve gas motion in a circumferential manner, as shown in Fig. 4 (Ref. 10). Radial and tangential oscillations are closely related but they can occur separately as well as in combination. Transverse mode frequencies can be calculated from the relation (Ref. 5 and 11)

$$f = \frac{(\alpha_{\rho\tau})a}{2R} ,$$

where f is the frequency, $\alpha_{\rho\tau}$ is a coefficient whose value is determined by the value of the radial mode number ρ and the tangential mode number τ, a is the velocity of sound in the gas, and R is the radius of the grain perforation. Values of the transverse mode frequency coefficient appear in Table 1.

Optimum placement of pressure transducers for detection of transverse mode oscillations presents a problem since the locations of the pressure antinodes follow the regression of the propellant web. The tangential mode is the most difficult to detect due to the difficulty in



(a) Radial Oscillations (b) Tangential Oscillations

FIG. 4. Transverse Mode Acoustic Oscillations Can Occur in Two Basic Modes. (a) Radial oscillations involve gas motion along radii as indicated by arrows. Locations of maximum pressure excursion are on the motor axis and the curved surface of the bounding cylinder. (b) Tangential oscillations involve circumferential gas motion indicated by arrows. Pressure maxima occur along lines on the cylindrical surface, which imposes stringent requirements for optimum pressure transducer locations.

TABLE 1. Values of the Transverse Mode Frequency Coefficient, $\alpha_{\rho\tau}$

$\tau \downarrow$ $\rho \rightarrow$	0	1	2	3
0	0.000	1.220	2.233	3.238
1	.586	1.697	2.714	3.726
2	.972	2.135	3.173	4.192
3	1.337	2.551	3.611	4.643

predetermining its orientation in the motor, and the restricted distribution of the pressure antinodes. In addition, this mode may rotate in circular perforations, making analysis of data more difficult. The usual approach in choosing transducer locations is to arrange a pattern on the motor, such that one location will always be near a pressure

antinode. A modification of a pattern suggested for liquid instability measurement appears to be suitable as it permits determination of the tangential mode orientation as shown in Fig. 5. (Ref. 12).

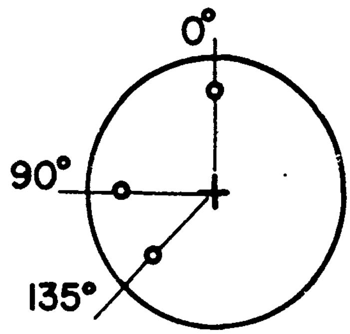


FIG. 5. Suggested Transducer Distribution to Provide Information on Orientation of Tangential Mode Acoustic Oscillations. Comparison of outputs from the three transducers will identify acoustic oscillations of all three types and will indicate the speed and direction of rotation of the tangential mode, if that should occur.

A pressure transducer location on the motor axis should be avoided. While such a location is suitable for detecting <u>any</u> longitudinal or radial mode, an axial location theoretically cannot detect <u>any</u> tangential mode.

NONACOUSTIC INSTABILITY

Nonacoustic instability (NAI) involves an interaction between the heated layer of the solid propellant, the combustion zone, and the gas discharge characteristics of the motor (Ref. 4 and 13). The frequencies encountered in this type of instability are generally below 100 cps, much lower than the frequencies of the natural acoustic modes of the motor. The pressure oscillations may be nonsinusoidal as in "chuffing" or they may be sinusoidal (Fig. 6). Nonacoustic theory treats only the sinusoidal oscillations. In both types of nonacoustic oscillation, the pressure fluctuations are a function of time only. There are no spacewise pressure variations. This class of instability poses little difficulty in measurement since the frequencies are low enough to be detected by the usual instrumentation and the location of pressure transducers is not critical.

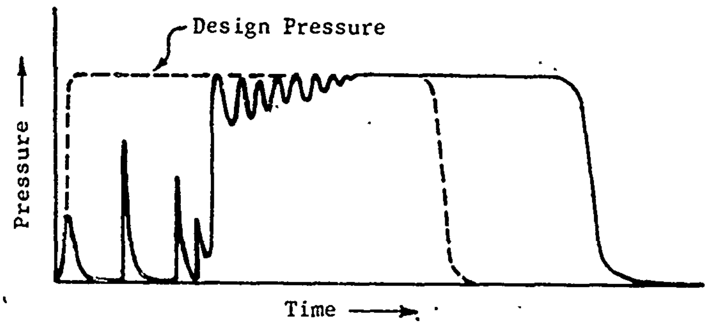


FIG. 6. Sketch of Typical Nonacoustic Pressure-Time History. Pressure spikes due to "chuffing" and sinusoidal oscillations are possible. Nonacoustic theory refers to the latter behavior.

CHARACTERISTICS AND CLASSES OF INSTABILITY

Knowledge of conditions under which particular classes of instability are likely to occur is helpful in anticipating the frequencies likely to be encountered in testing. Motor instability, however, depends on the relative magnitude of a number of factors which include ability of the combustion to amplify pressure and flow disturbances, effect of mean flow in generating or damping disturbances, energy losses induced by solid particles suspended in gas, the influence of the nozzle on acoustic losses, and the participation of the propellant grain in absorbing acoustic energy (Ref. 2, 14 & 15). Some of these factors can be calculated and several are being routinely evaluated in laboratory experiments but a reliable method of predicting motor instability behavior remains for the future (Ref. 16).

Laboratory test techniques that are available for rating instability characteristics include measurement of combustion amplification of flow disturbances and the effect of motor geometry on acoustic losses (Ref. 17-19). Combustion amplification tests are conducted in "T-burners" which normally test the pressure-coupled amplification characteristic (Ref. 20-22). A recent modification to the basic T-burner design permits investigation of velocity-coupled amplification (Ref. 23).

Although complete characterization of rocket motor instability behavior is not yet possible on a quantitative basis, classes of instability can be identified and a general discussion made on the basis of past experience and knowledge of the several definitive tests that are presently available (Ref. 2 and 15). For this purpose combustion instability will be classified into three regions on the basis of frequency.

HIGH FREQUENCY INSTABILITY (HFI)

This class of instability involves frequencies from 1,000 to over 50,000 cps. It normally occurs in transverse acoustic modes but is readily stabilized by solid particles in the gas. High frequency instability is likely to be a problem in motors with circular (or nearly circular) grain perforations, with smokeless propellants, and with very high energy compositions. Stability may be achieved in these cases by introduction of a stabilizing rod or by designing the proper convolutions into the grain perforation, both of which will tend to interfere with the acoustic gas motion and will usually reduce or eliminate the instability. It should be noted that radial and mixed modes are rarely, if ever, seen in solid propellant rocket motors. Transverse oscillations occur most often in the first tangential mode.

Consideration of the interaction between the solid propellant web and transverse mode gas oscillations indicates that acoustic energy losses into the solid at certain times during burning can be large enough to damp instability (Ref. 24-26). This explains in part the observations concerning the appearance and disappearance of transverse modes at various times during a firing. Transverse modes are more likely to be encountered late in burning due to two other factors: (1) the star points have largely burned away and (2) stabilizing rods occupy a smaller percentage of the cavity.

INTERMEDIATE FREQUENCY INSTABILITY (IFI)

Intermediate frequency instability includes the frequency range of 100 to 1,000 cps. It most commonly occurs as longitudinal (axial mode) oscillations and in rocket motors with large length to diameter ratios. This class of instability is also seen with heavily metallized propellants. Solid particle damping is relatively ineffective in the frequency ranges encountered and evidence suggests that the presence of metal in the combustion process may even contribute to this class of instability. The frequencies of oscillation are close to those calculated by assuming gas motion in a chamber closed at both ends. The influence of the nozzle is important in that it tends to stabilize axial instability. Acoustic tests in model rocket motors show that the nozzle losses vary in proportion to the nozzle throat-to-grain port area ratio (J). Observations in rocket motor firings indicate that motors which were stable early in burning may become unstable later in the firing, which appears to be due, at least in part, to a decrease in the J-factor (Ref. 27).

Another feature of axial mode IFI is the importance of velocity coupling, in contrast to pressure coupling which tends to dominate in the other ranges of instability. Velocity coupling causes a nonsinusoidal distortion of the pressure oscillations and it may be accompanied by a threshold velocity requirement such that a flow disturbance above a limiting level may be required in order for axial mode instability to persist

(Ref. 2, 15, 28, 29 and 30). Such behavior offers a perplexing situation to motor design and test personnel for an apparently stable motor may suddenly become unstable following any finite disturbance in the motor (Fig. 7).

Axial mode instability has only recently come under study. Much remains to be learned of this complex phenomenon.

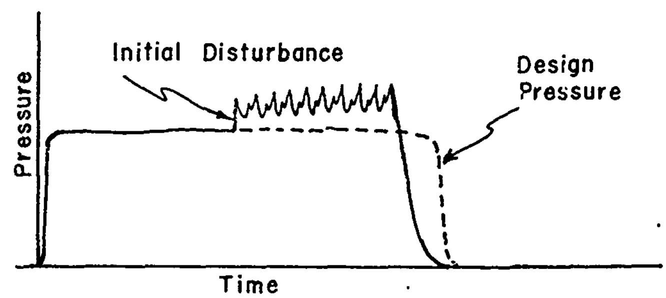


FIG. 7. Sketch of Motor Pressure During Axial Mode Intermediate Frequency Instability. Requirement of a triggering pulse is sometimes encountered in this class of instability. Another characteristic is the presence of periodic, nonsinusoidal oscillations, which are caused by velocity-coupled combustion-flow interaction.

LOW FREQUENCY INSTABILITY (LFI)

Low frequency instability generally occurs at frequencies below 100 cps and it includes nonacoustic and acoustic oscillations.

Nonacoustic instability depends on the relative thermal wave thickness in the propellant and the internal volume to nozzle throat area ratio (L*) (Ref. 4). This type of instability is most likely to occur in motors with a high propellant load ng factor and designed to operate at low pressure (low burning rate) (Ref. 2 and 15). Laboratory experiments with small motors that oscillate nonacoustically have provided stability limit data for metallized and nonmetallized propellants (Fig. 8) (Ref. 31). It remains to be determined, however, that the small motor data is capable of predicting larger motor behavior.

Interest in low frequency acoustic instability has grown recently due to the possibility of its occurrence in very large rocket motors. Present knowledge of this class of instability comes almost entirely from large T-burner tests (Ref. 32 and 33). It can occur with heavily metallized propellants since solid particle damping is ineffective at the low frequencies encountered. Instability with metallized propellants can also show a "preferred frequency" behavior in which instability occurs

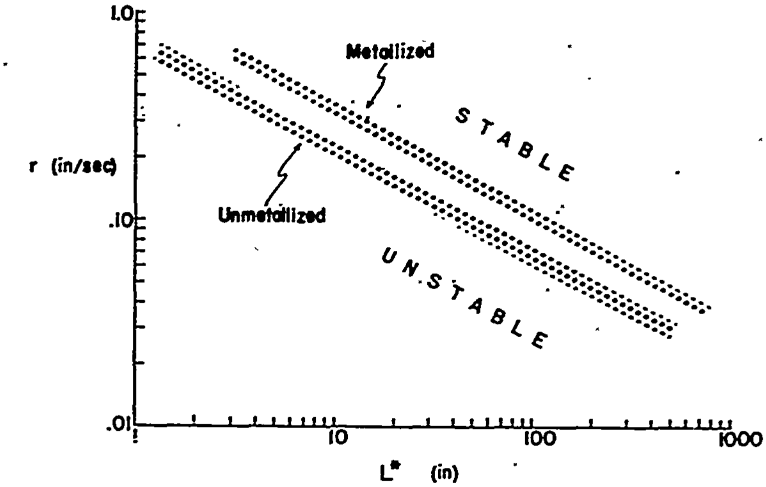


FIG. 8. Nonacoustic Stability Data From a Small Research Motor. Comparison of this data with larger motor behavior may result in this information being useful in predicting conditions for stable motor operation.

over a narrow range of frequency at a given pressure (Ref. 34). Similarities in the mechanism between low frequency varieties of nonacoustic and acoustic instability has brought forth attempts to describe both aspects with a single theory.

The high cost of testing full scale motors of the sizes planned for boosting outer space missions puts great emphasis on development of laboratory techniques and theory which can be applied to prediction of LFI.

INSTABILITY MEASUREMENT PROBLEMS

DETECTION OF INSTABILITY

In a general sense, any physical property related to combustion-driven gas oscillations can be used to determine the presence of instability and to identify the modes. Motor case strain, acceleration of motor components, motor thrust variations, and measurement of the acoustic field outside the motor offer the possibility of detecting instability and of correlating the effect of instability on these aspects of motor behavior (Fig. 9) (Ref. 35). Detection of instability is better accomplished, however, by using pressure transducers chosen especially for that purpose. The pressure transducers routinely used on motor firings are seldom suitable for detecting pressure oscillations because they lack the frequency response. This is not too serious in detection

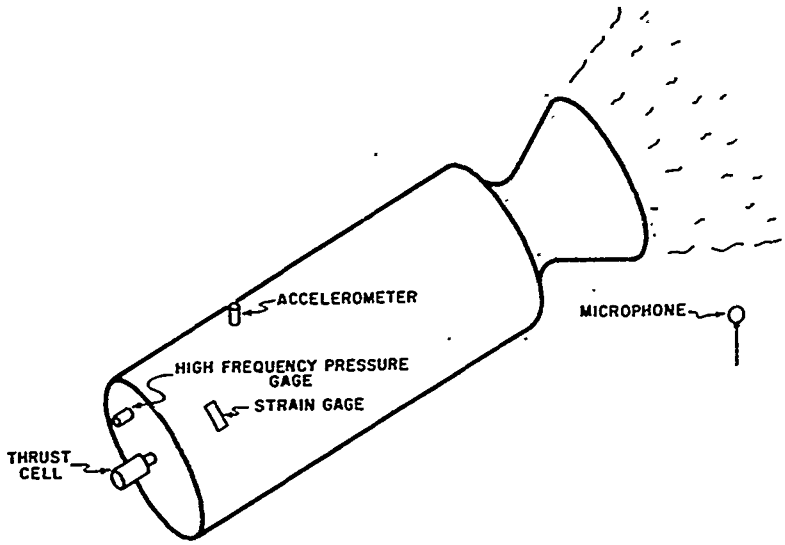


FIG. 9. Various Methods that can be Used to Detect Combustion Instability. Measurement of gas pressure oscillations is the most direct and the best developed of all methods.

of LFI but it becomes more acute when one encounters IFI and HFI where use of the proper transducer becomes a necessity if meaningful measurements are to be made (Ref. 36).

Pressure transducers are commercially available which permit measurements from dc to frequencies exceeding 50,000 cps. They characteristically feature an external mounting thread and a flush sensing diaphram (Fig. 10). Model variations are available that are either uncooled or water cooled. A relatively new type is available in which a flow of helium cools the transducer and serves to communicate between the gas in the motor and the sensing area in the transducer (Ref. 12). The preferred mounting of high frequency pressure transducers is an arrangement such that the sensing area is flush with the inner motor wall. While this is desirable from a frequency response standpoint, it is out of the question for uncooled transducers and may even be hazardous to those with cooling. The usual solution to the heating problem is to recess mount the transducer and utilize a grease or other insulating medium that will communicate the gas pressure to the sensing area. While solving the heating problem, recess mounting does affect the frequency response (Ref. 36 and 37). An alternate method of heat protection that may not cause the problem of frequency response degradation is the application of an ablative material to the face of the transducer. Synthetic rubber discs of thicknesses up to one-fourth inch have been used with apparent success.

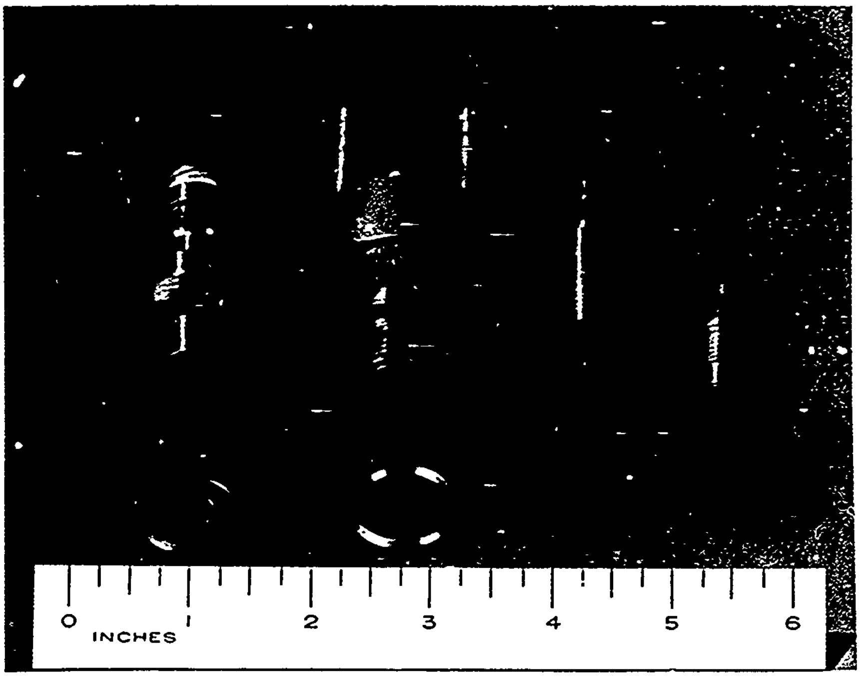


FIG. 10. Typical High Frequency Response Pressure Transducers. External mounting threads and a flush sensing diaphram are characteristics of these devices. Water cooled transducer diaphram is a necessity for flush mounting in a rocket motor.

SIGNAL CONDITIONING AND RECORDING

Problems of signal conditioning and recording include filtering and amplification of high frequency pressure transducer signals, choice of recording techniques and knowledge of frequencies likely to be encountered during the test.

The use of filters to provide high-pass, low-pass, and band-pass characteristics is nearly always required in HFI and IFI measurements (Fig. 11). High-pass filters are needed to block the dc signal component caused by mean pressure in the motor. This permits small amplitude signals from pressure oscillations to be amplified to a useable level, yet avoids saturating the recording equipment with an excessive dc signal. The low-pass filter is used to provide a "clean" pressure-time history from the high frequency transducer. The high-pass and low-pass signals can be advantageously recorded on a dual beam oscilloscope to provide a quick-look record within seconds after a motor firing (Fig. 12) (Ref. 35 and 36). Low-pass filters for such applications can be simple devices constructed from passive components with the cutoff frequency somewhat below the first longitudinal mode. Band-pass filters are useful in cases where several modes are present during a firing. Each band is set to pass a particular portion of the frequency spectrum so that

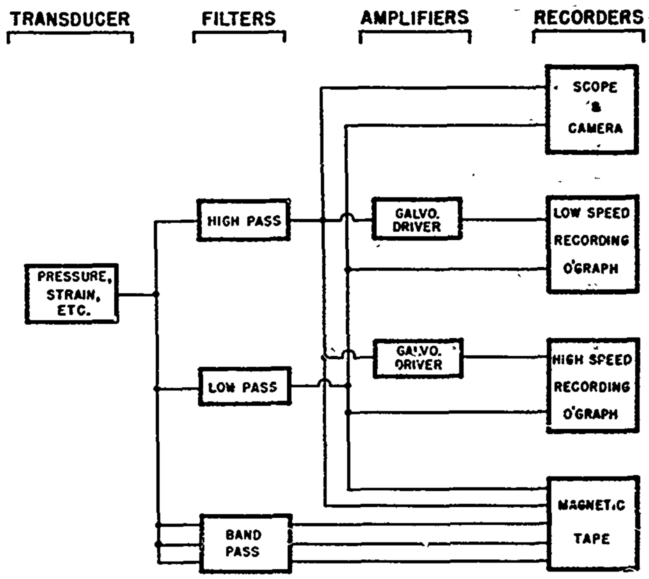


FIG. 11. Instrumentation of a Typical High Frequency Channel for Instability Measurement. Filters split the signal up into more easily handled and interpreted segments. Multiple band-pass filters are useful for dividing a complex signal into discrete frequency segments so that real-time recorded data can be analyzed for frequency and amplitude variations as a function of time during burning.

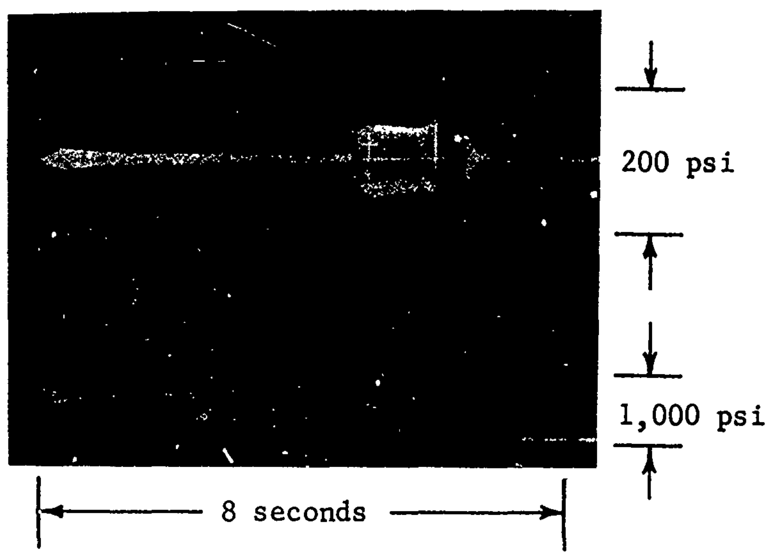


FIG. 12. Oscilloscope Camera Record Taken During a Motor Firing That Exhibited Axial Mode Intermediate Instability. Pulse fired into motor at 4.8 seconds initiated instability. This type of record is useful for quick-look purposes and provides a compact, conveniently handled and stored history of motor firings.

frequencies and amplitudes of the various modes are separately displayed (Ref. 36).

The use of filters requires some knowledge of the frequencies likely to be generated in the motor. The equations for acoustic vibrations (given in the section entitled Nature of Combustion-Driven Gas Oscillations) can be used but uncertainties often arise in judging the cavity dimensions of motors with complex internal geometries. The nature of this problem is that unexpected frequencies may be encountered because the gas oscillated in a different manner than predicted. Solution of this problem is to provide at least one channel with broad frequency response. This has the disadvantage that signals with widely varying amplitudes may be either saturated or lost in noise. Use of a logarithmic voltage compressor in such instances offers the possibility of recording a wide range of amplitudes without exceeding the recorder's limits.

Three types of recording devices that find application in other measurement work are utilized for gathering instability data. The major concern is to assure that the recorder does not unduly limit the frequency response. In the case of long sweep time on the oscilloscope, of course, frequency response is not really an issue as a resolution of about 50 lines per inch on the screen is the maximum capable of being observed. Recording oscillographs offer a convenient means of recording data and frequency response can be as high as 13,000 cps. All high frequency galvanometers, however, need the proper driver amplifier as they require more power than most instrumentation provides. Oscillographs have the disadvantage of requiring high paper speeds if high frequency response is to be achieved. Another disadvantage is that the data is in graphical form and the analysis of complex waveforms from such records is tedious if not impossible. Many of the objections to recording oscillographs are solved by magnetic tape recorders. In fact, these recorders exceed all others for frequency response and duration of recording time. Use of magnetic tape data is particularly desirable if any extensive analysis of high frequency data is to be done. Ability to reproduce the electrical signal also has advantages in that the signal can be played back, filtered, and re-recorded on an oscillograph. In this manner, information that was originally recorded incorrectly on the oscillograph can be retrieved.

METHODS OF ANALYSIS

Analysis of data comprises determination of frequency and amplitude of the oscillatory component and the time of occurrence of particular oscillations during burning. Characteristics of several methods of analysis appear in Table 2. Analysis of graphical data acquired at low recording speed is limited to determination of amplitude and occurrence of oscillations as a function of time. No information concerning frequency is available from such records except possibly in the case of LFI. High speed oscillograph records, on the other hand, can be assessed for frequency but the degree of success in frequency-amplitude determination

TABLE 2. Methods of Analysis

TYPE OF DATA & ANALYSIS		CHARACTER OF INFORMATION
GRAPHIC RECORDS	LOW SPEED	AMPLITUDE & TIME - LOW FREQUENCY RESOLUTION
	HIGH SPEED	AMPLITUDE, TIME, & FREQUENCY TO ~ 12kc
MAGNETIC TAPE	TIME SCALING	SAME AS ABOVE - FREQ. DEPENDS ON SCALE FACTOR
	SPECTRUM ANAL.	AMPLITUDE & FREQUENCY - NO TIME RESOLUTION
	SONIC ANAL.	CONTOUR MAP OF AMPLITUDE, FREQUENCY & TIME

depends on the complexity of the signal. Signals which are composed of several frequencies at various amplitudes are difficult to assess accurately. Graphical methods for attaining a frequency-amplitude analysis are available but archaic in light of modern methods utilizing magnetic tape and electronic instruments for the task.

Capability to recreate the electrical impulses generated during the test offers a variety of approaches for analysis of data. The methods used in analysis of instability data are similar to those used in acoustics and vibration studies and depend on magnetic tape playback of the test signal. Tape signals can be analyzed by octave or third octave band, multiple band-pass with oscillograph recording to provide time resolution, electronic spectrum (heterodyne analyzer), and sonic analyzer techniques (Ref. 35, 36 and 38). Some of these methods require costly, specialized equipment and their use depends to a great extent on the nature of the data, the speed with which detailed analysis is required, and the ultimate utilization of the information.

CONCLUSION

Measurement of combustion instability manifestations presents a variety of problems ranging from selection of transducer locations to choice of data analysis methods. Success in making instability measurements depends largely on using a systematic approach which includes the following steps:

1. Expect instability on every motor firing, especially following motor design, grain design, or propellant composition changes.

2. Calculate frequencies of the first longitudinal and first tangential acoustic modes.

3. Provide instrumentation and transducer mountings that will detect and record signals through the first tangential frequency. A single broad frequency response channel is often adequate for instability monitoring purposes.

Unfortunately, not all rocket motor firings are equipped with instrumentation which is suitable for instability measurement. While it is recognized that instability is only one of a large number of problems facing motor development engineers, instability is encountered often enough that plans should be made to provide every motor firing with some capability for instability measurement. Such provision is insurance against having to refire a motor in order to determine whether or not instability was the cause of anomalous behavior and will usually pay for itself in the time and money saved.

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